

# BPM Signal Processing: A Cartoon View

Rob Kutschke

Oct 13, 2003

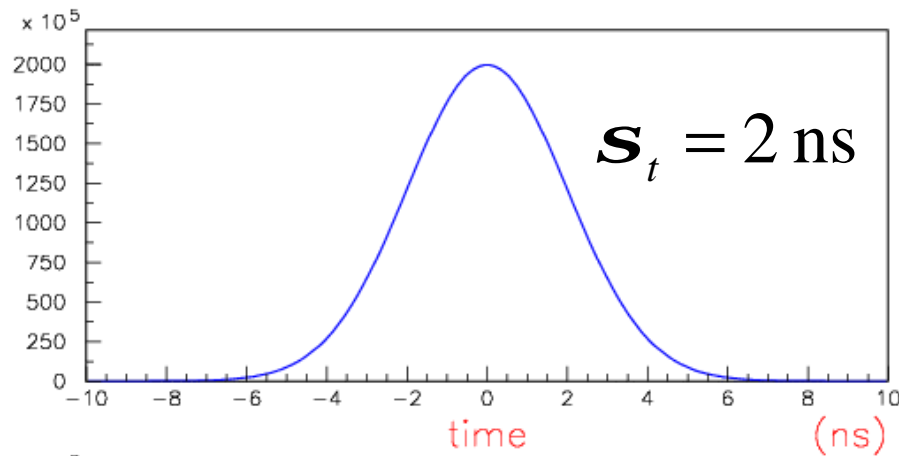
# Outline

- Reminder about notation.
- Reminders about Fourier Transforms (FT).
- Bunch shape.
- Response of resonant filter to a single pulse.
- Response of resonant filter to multiple pulses, batch mode and bunch mode.
- A proposal about how to analyze the output of the resonant filter.

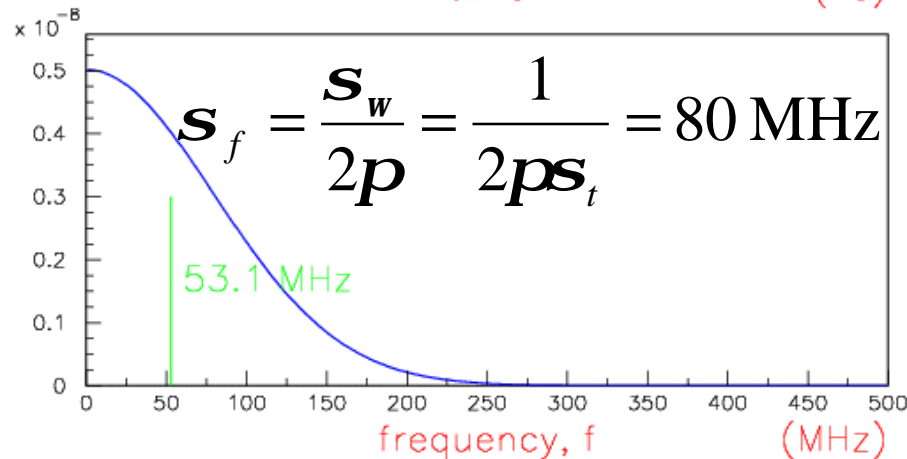
# Reminder about Notation

- $F(t) = \sin( 2\pi f_0 t ) = \sin( \omega_0 t )$
- Frequency:  $f_0$
- Angular frequency:  $\omega_0 = 2\pi f_0$
- Period:  $T_0 = 1/f_0 = 2\pi/\omega_0$
- When someone says “frequency” they usually mean  $f_0$  but sometimes they mean  $\omega_0$  !

# FT of a Gaussian is Gaussian

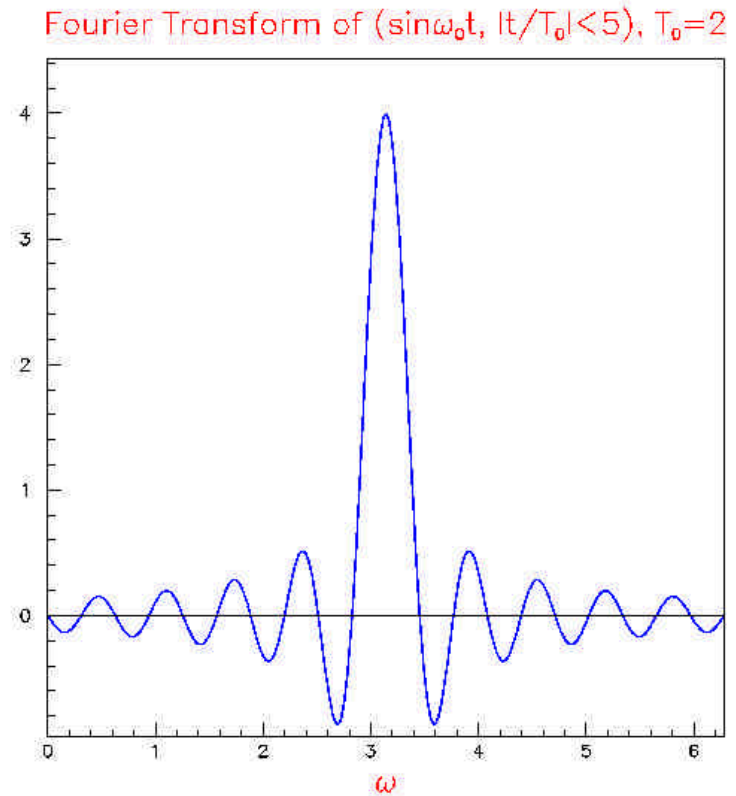
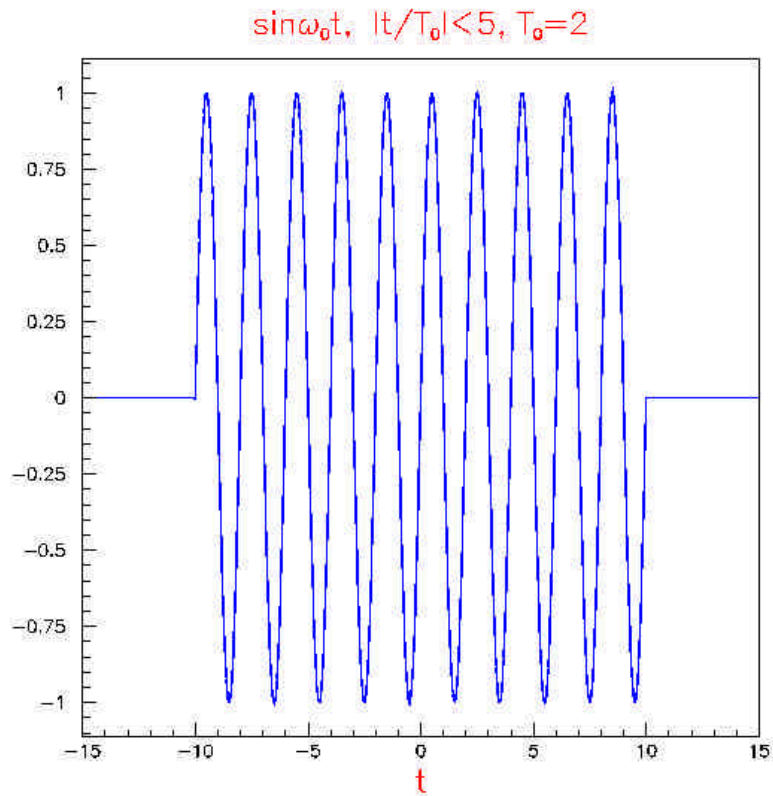


Bunch shape



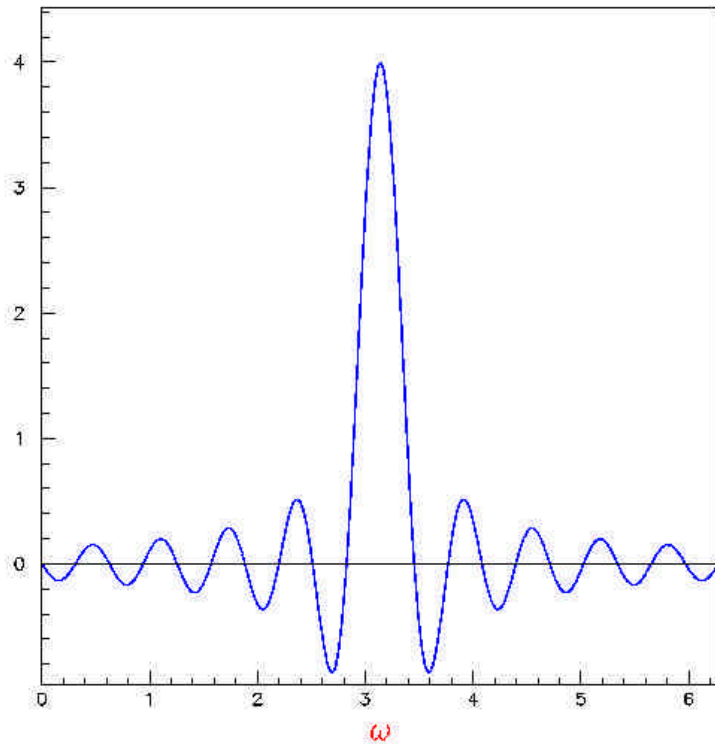
Power spectrum of a single bunch passing a fixed point.

# FT of Finite Wave Train



# FT of Finite Wave Train

Fourier Transform of  $(\sin \omega_0 t, |t/T_0| < 5)$ ,  $T_0=2$



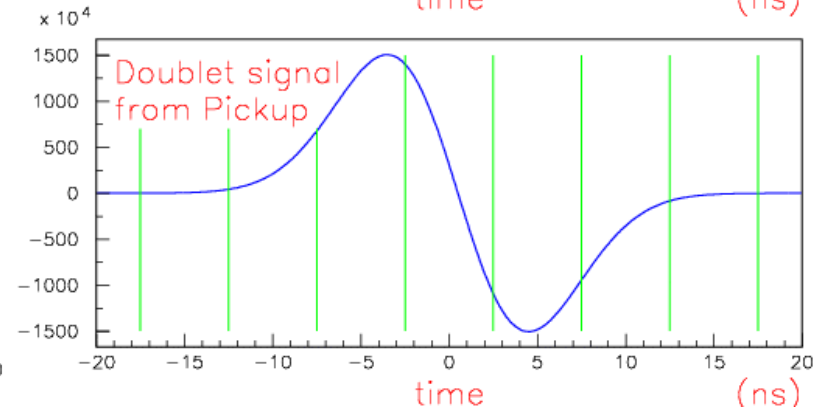
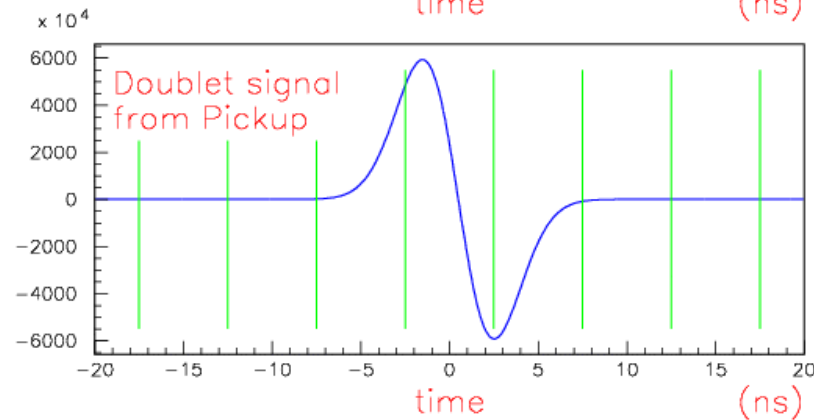
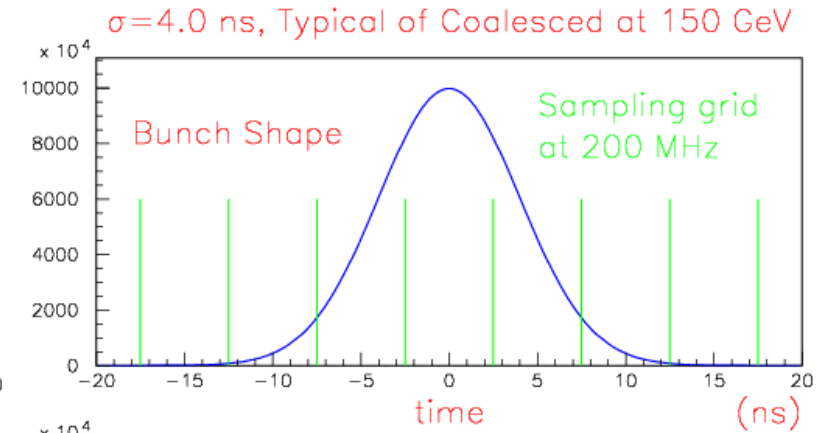
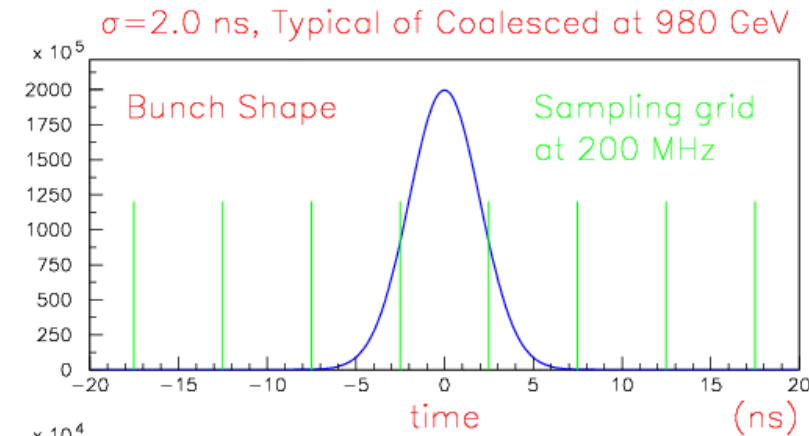
- Define  $N$  = number of oscillations in the time domain ( = 10 here ).
- First zero of FT at  $(\delta\omega/\omega_0) = \pm 1/N$  ( $\omega_0 = \pi$  ).
- Equivalent statement: zero occurs when the number of oscillations in the interval differs by  $\pm 1$ .

# Bunch Shapes

- Shape of a single bunch is nominally a Gaussian.
- Nominal scaling of bunch length is  $1/\sqrt{E}$  but this is not achieved.
- Coalesced bunches:
  - $\sigma \approx 4$  ns at 150 GeV ( injection energy )
  - $\sigma \approx 2$  ns at 980 GeV
- Uncoalesced bunches
  - About 1/9 as many particles/bunch.
  - $\sigma \approx 2$  ns at 150 GeV ( injection energy )
  - $\sigma \approx 1$  ns at 980 GeV

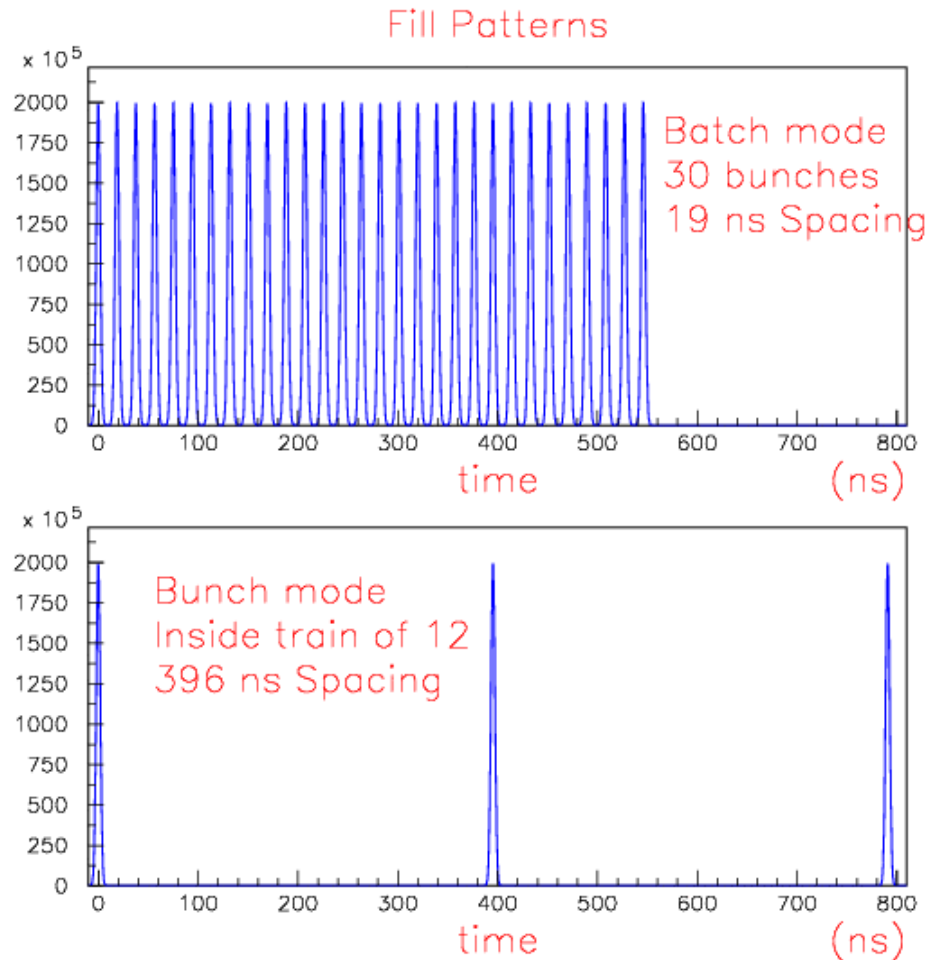
# Coalesced vs Uncoalesced

- Coalescing: take  $n$  bunches, separated by 19 ns and put them on top of each other.
  - Typically  $n=9$ .
  - Nominal behaviour:
    - Number of particles in the coalesced bunch is  $n$  times the number in each uncoalesced bunch.
    - Time width of bunch scales like  $1/\sqrt{E}$ 
      - Ideal case usually not achieved.



- Is  $\approx 200$  MHz is fast enough to digitize pulse with no shaping?
- A and B plates must be digitized at same time: time difference implies a position error.

# Three Fill Patterns of Interest



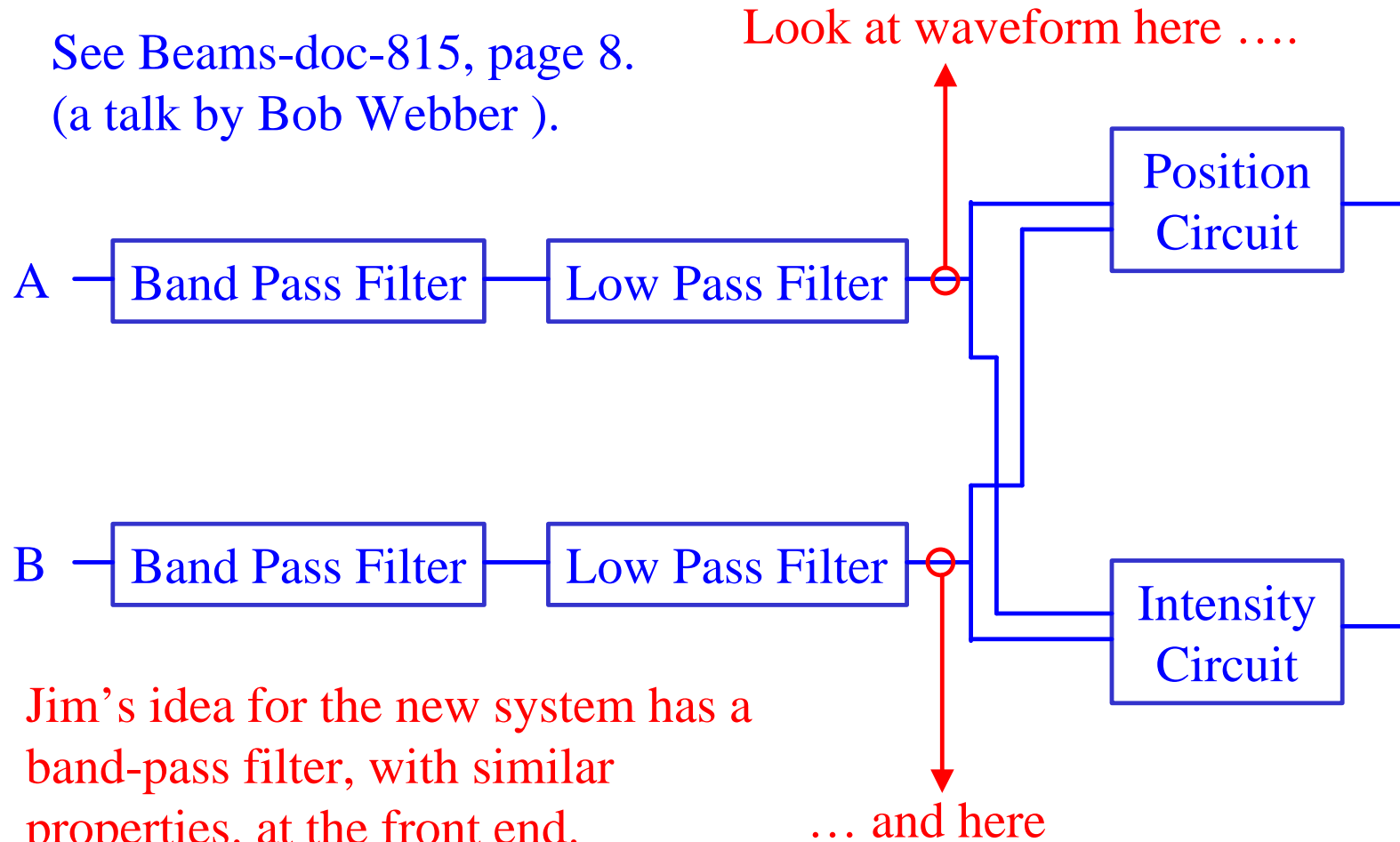
- Third pattern is just a single bunch in the machine.
- The single bunch is the only pattern for which “first turn” measurements need to be made.
- For other patterns we need only measure steady state conditions.

# Cartoon of Our Options

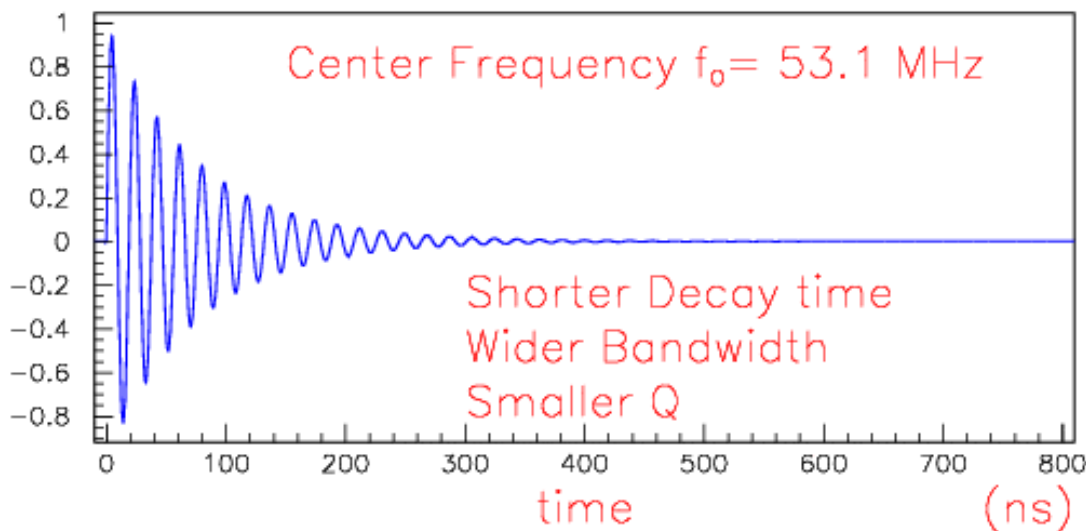
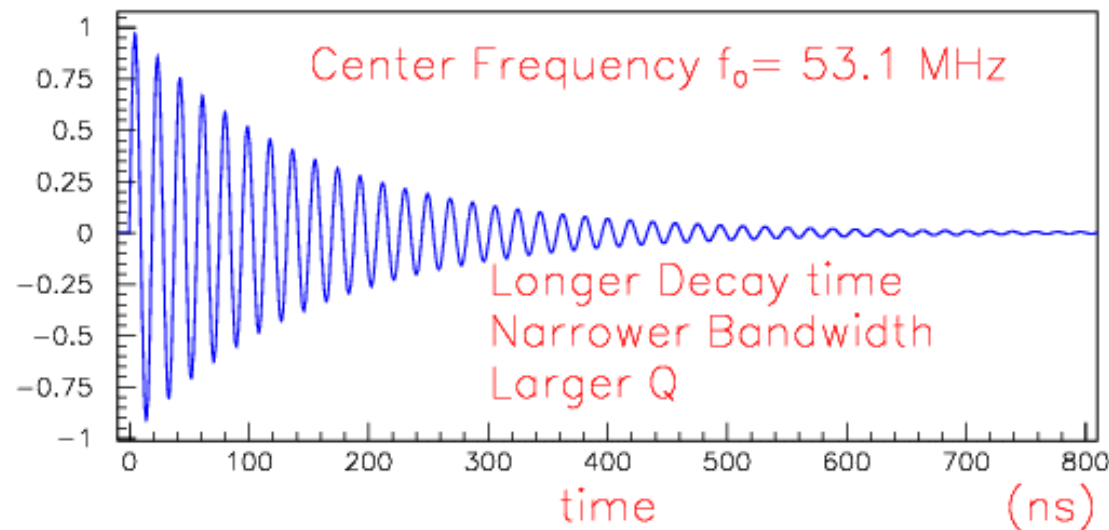
- Superfast digi, no shaping ( 2 GHz or more ).
  - Very expensive.
- Shape the pulse ( Digitize once or many ).
  - Need to work hard at timing? Especially on first turn?
  - Tradeoff: long pulse good for precision and accuracy but bad for separation of protons and anti-protons.
    - How to deal with batch mode when bunches are 19 ns apart?
- Ring resonant filter and transfer position info to the frequency domain.
  - Coherent addition of bunch signals is natural.
  - Give up single bunch resolution.

# Existing RF Module

See Beams-doc-815, page 8.  
(a talk by Bob Webber ).

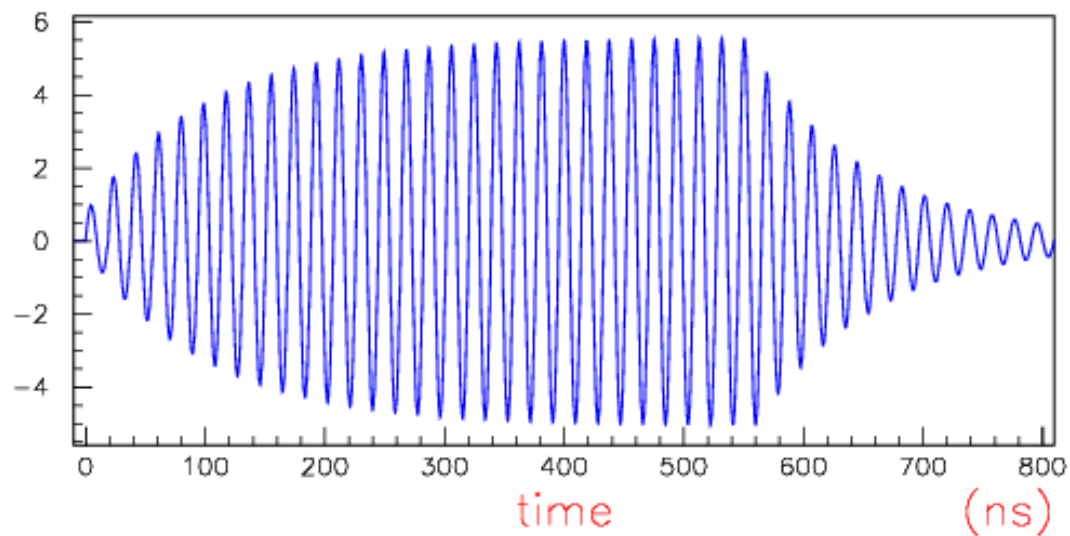
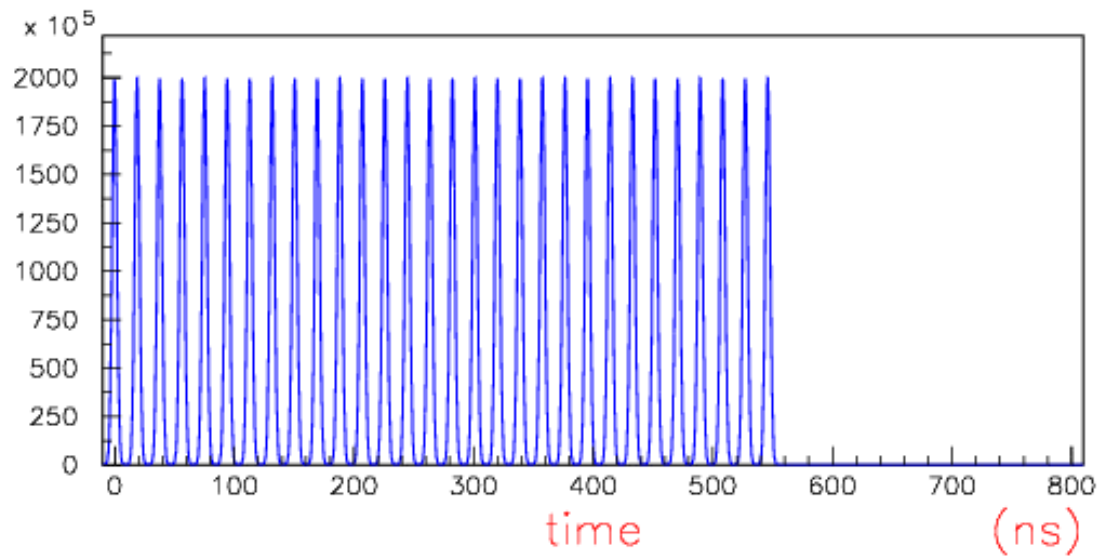


## Cartoon Impulse Response of Resonant Filter

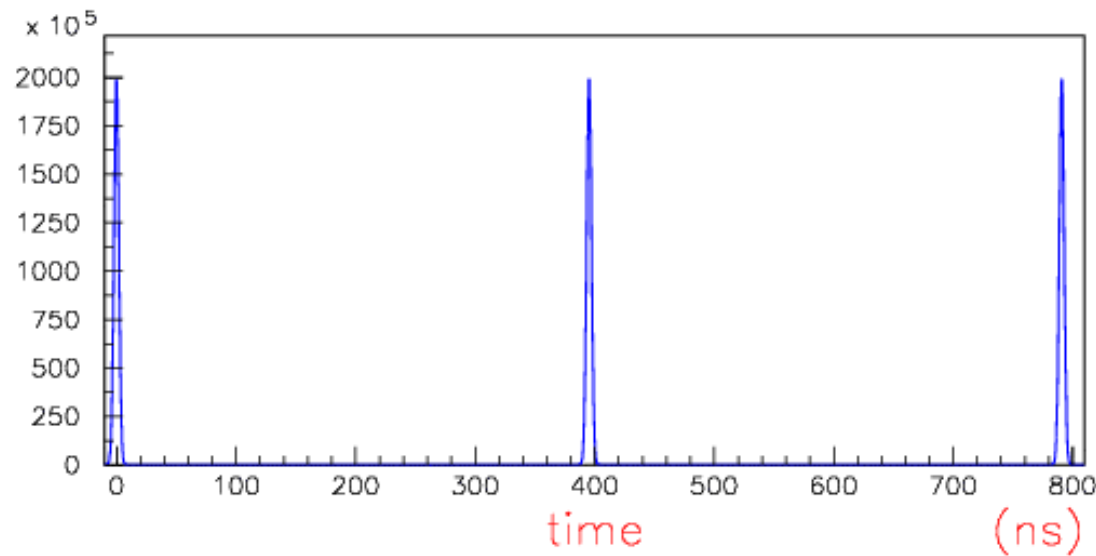


Cartoon shows the 53.1 MHz component only. The true signal will be complicated by other frequencies inside the band-pass.

Why 53.1 MHz?  
How many rings do we want/need?  
Answers later.

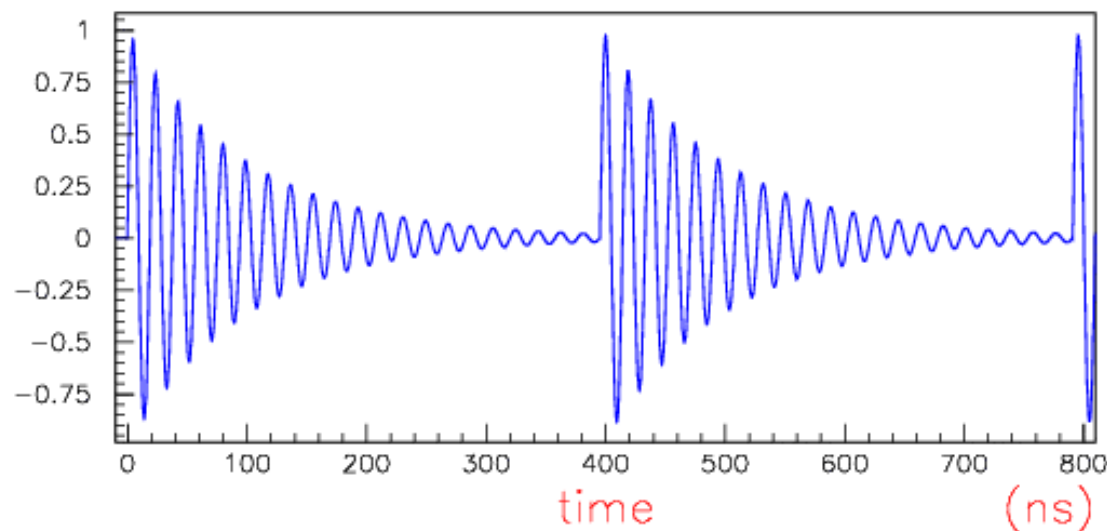


- Bunch pattern in batch mode.
- Bunches are uncoalesced.
- Cartoon response of the resonant filter, to the above batch of bunches.
- Existing BPM electronics designed to use this signal.



- Bunch pattern in “bunch mode”, 396 ns between bunches in a train.

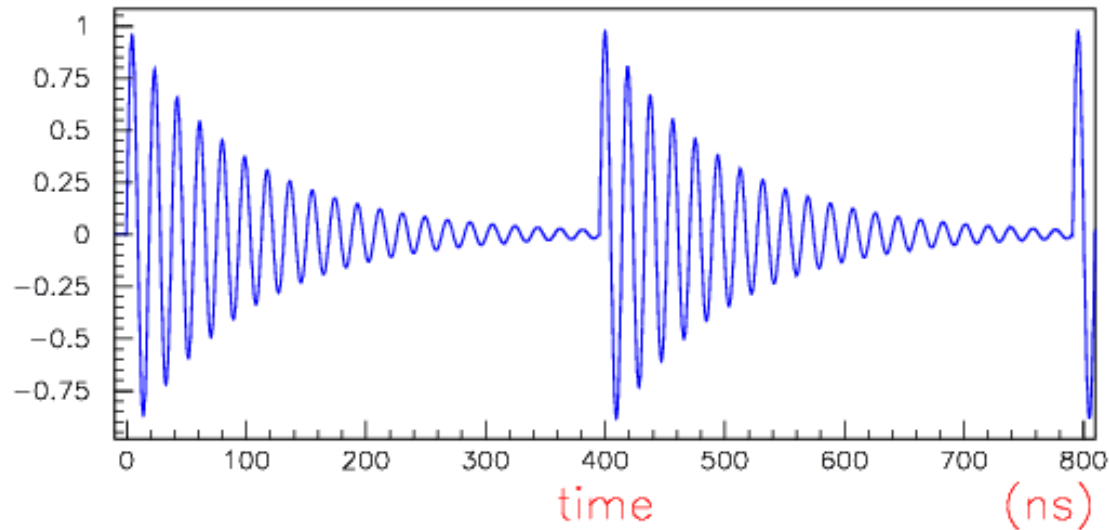
- Bunches are coalesced.



- Cartoon response of the resonant filter, to the above batch of bunches.

## Comment on 53.1 MHz

- The 53.1 MHz component of the filter is kicked in phase by each passing bunch.
  - Also true for harmonics of 53.1 MHz.
- All other frequencies will be excited out of phase by each bunch.
  - Wave form at these frequencies is more complex and either we lose information or we need fancier signal processing.
- Following slides will talk about extracting the information at 53.1 MHz.



- How to process the above waveform to get a position?
  - A and B signals differ in amplitude.
- For now, consider just protons or anti-protons in the machine.
- Also assume no significant reflections.

# First Turn Mode

- Needs to work only for one bunch in the machine.
- For each of A and B signals:
  - Digitize at  $\approx 200$  MHz.
  - Compute FFT of digitized time series.
    - Integration time can be as long as a full turn if the filter output after one turn is still above the noise and least count.
    - Long integration time = narrow band.
  - Output of FFT is the power in a frequency band centered at 53.1 MHz. **This is A or B.**
- $\text{Position} = (A-B)/(A+B)$

# Question

- I think that a long integration time in the FFT implies more precise values of A and B, which implies more precise position? Is this right?
- At the same time, it changes the meaning of A and B since the bandwidth decreases.

# Turn by Turn Mode

- Requirements say that it is OK to average over bunches:
  - How many?
  - Report this average on each turn.
- Must work with all fill patterns:
  - Single bunch
  - Batch
  - Bunch ( 3 trains of 12 bunches )
  - Others we might dream up later.

# Turn by Turn mode

- Works as for first turn but the integration time window of the FFT may be changed.
  - Might integrate over signal from one bunch, from several, ... up to all 36 bunches.
    - Integration over several bunches produces some sort of average position.
  - Question: if there are no bunch to bunch diseases, does accuracy improve if integration time is longer?

# Closed Orbit

- Must work for all fill patterns.
- As before but integration time of FFT is many turns.
  - This averages out the betatron oscillations.
- Questions:
  - If we integrate a long time the bandwidth narrows - can we lose important information located in the sidebands? Maybe A becomes a histogram covering a range of frequencies, not just a single number. Then do peak finding on it?

# What About Anti-Protons?

- For now, consider proton signal corrupting the anti-proton measurement.
- When the anti-proton intensity problems are solved, we will also need to worry about the antiprotons corrupting the proton measurement.

# What About Anti-Protons?

- Now we get a waveform from each end of each plate. Processes each the same way as described before.
- In the limit of perfect directionality, we directly measure:  $A_P$ ,  $A_{Pbar}$ 
  - Real numbers, the output of each FFT.
- For imperfect directionality, the observed numbers are contaminated with each other.

# Imperfect Directionality

- Define two feedthrough coefficients:  $\epsilon_1, \epsilon_2$ .
- Also need to know relative phase,  $\delta$ , between proton and pbar waveforms.
  - Depends on state of cogging.
- These differ from one BPM to the next.
- The instrument measures:

$$\mathbf{a}_P = \left| A_P + \mathbf{e}_1 e^{i\delta} A_{Pbar} \right|$$

$$\mathbf{a}_{Pbar} = \left| A_{Pbar} + \mathbf{e}_2 e^{-i\delta} A_P \right|$$

# Imperfect Directionality

$$\mathbf{a}_P = \left| A_P + \mathbf{e}_1 e^{i\mathbf{d}} A_{Pbar} \right|$$

$$\mathbf{a}_{Pbar} = \left| A_{Pbar} + \mathbf{e}_2 e^{-i\mathbf{d}} A_P \right|$$

- Measure  $\alpha_P$  and  $\alpha_{Pbar}$ , to get two equations and two unknowns.
  - Solve for  $A_P$ ,  $A_{Pbar}$ .
- Need to know  $\varepsilon_1$ ,  $\varepsilon_2$ , and  $\delta$  for each BPM and each cogging.
- Similarly to extract  $B_P$ ,  $B_{Pbar}$ .

# Questions

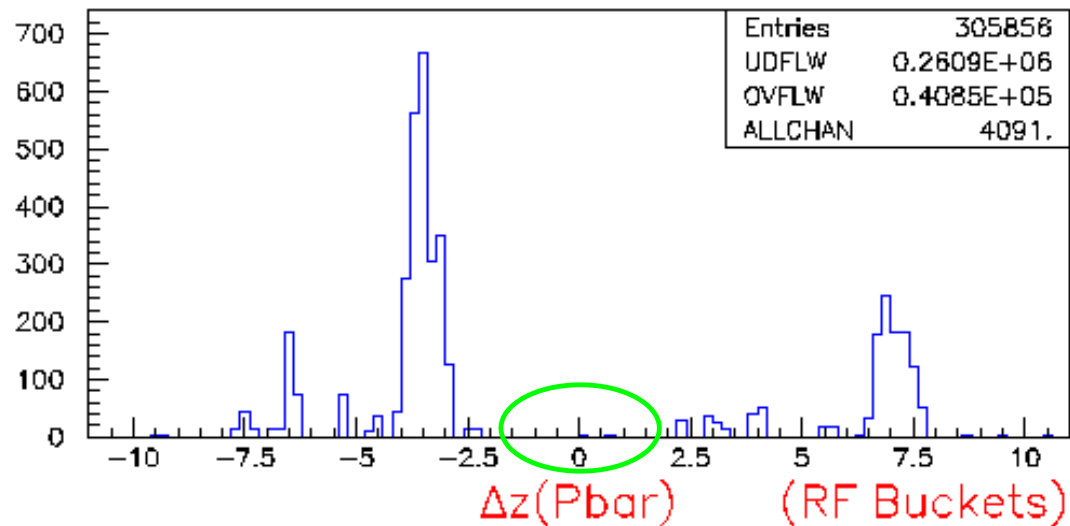
- The 2-species response also depends on the relative phases of the betatron and synchrotron oscillations of the  $p$  and  $pbar$ ? Is this a significant effect? Is it stable? Is it repeatable from store to store?
- Closed orbit is probably immune from this regardless of its size, but not turn by turn?

## Second Comment on 53.1 MHz

- Could this work with other frequencies ?
- Sure, but.
  - Only at 53.1 MHz and its harmonics is the interference between bunches in phase for all fill patterns.
  - At other frequencies, some fill patterns will excite destructive interference, which reduces the sensitivity of the measurement.
- Could do 53.1 MHz for batch mode and  $53.1/21$  MHz for bunch?

## Back to Short Pulse

- The alternative to the ringing filter is to stretch the pulse out a little and then sample it ( either single measurement or 200 MHz sample ).
- Tightest time window is set by proton antiproton separation.

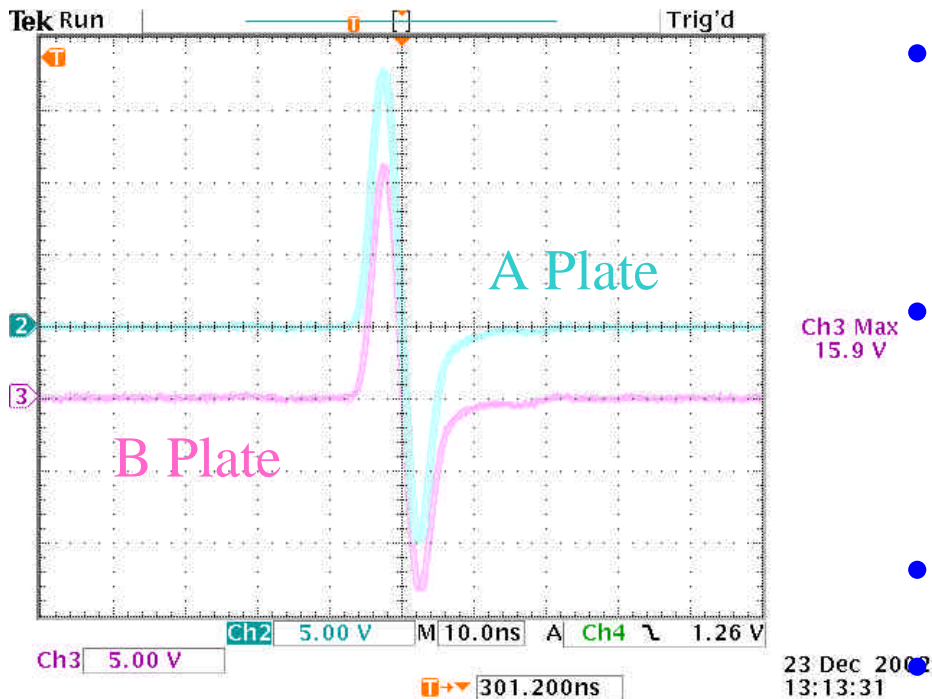


- For each BPM, compute arrival time of proton bunch.
- Compute position of all antiproton bunches at that time.
- Plot position difference of P and Pbar.
- Above figure:
  - For “Collision Point Cogging”, P1=A1 at F0.
  - Not sure of sign.
- Only 6 instances with separation  $< 2.35$  buckets ( 44.5 ns ).

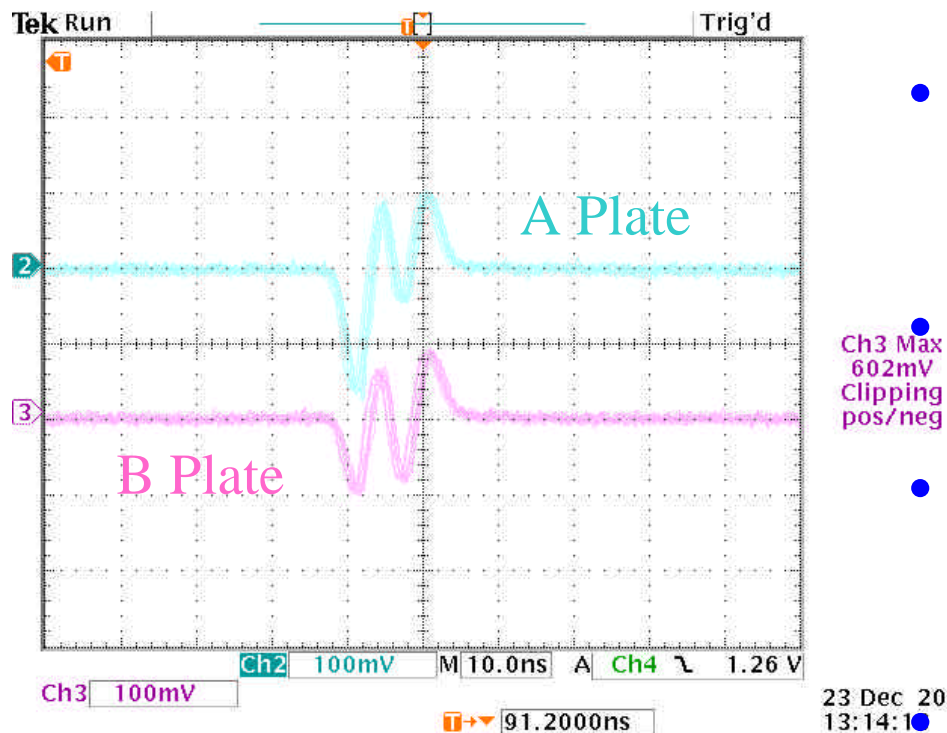
# P/Pbar Overlaps for Collision Point Cogging

BPM	Proton	AntiProton
HPA0U	1	13
HPA0U	25	25
HPB0U	1	25
VPA0U	1	13
VPA0U	25	25
VPB0U	1	25

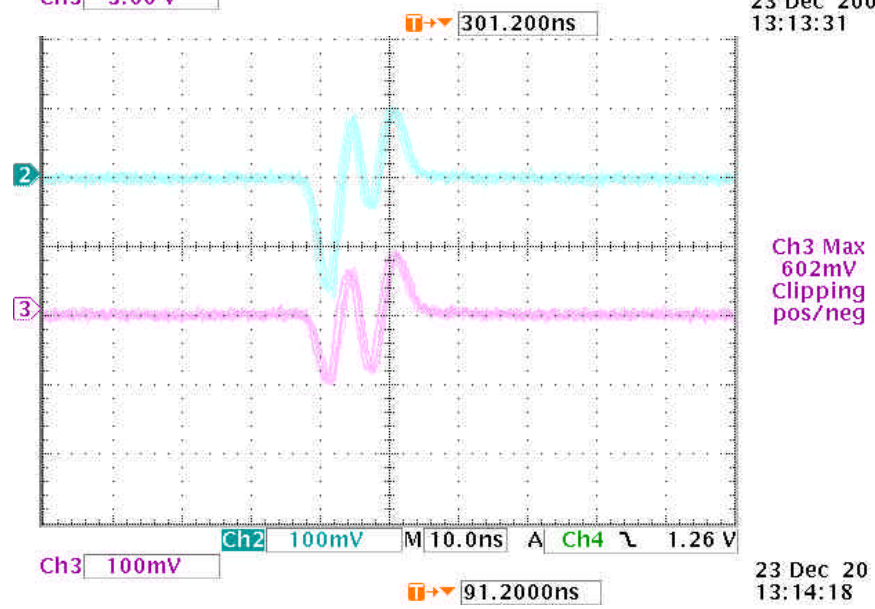
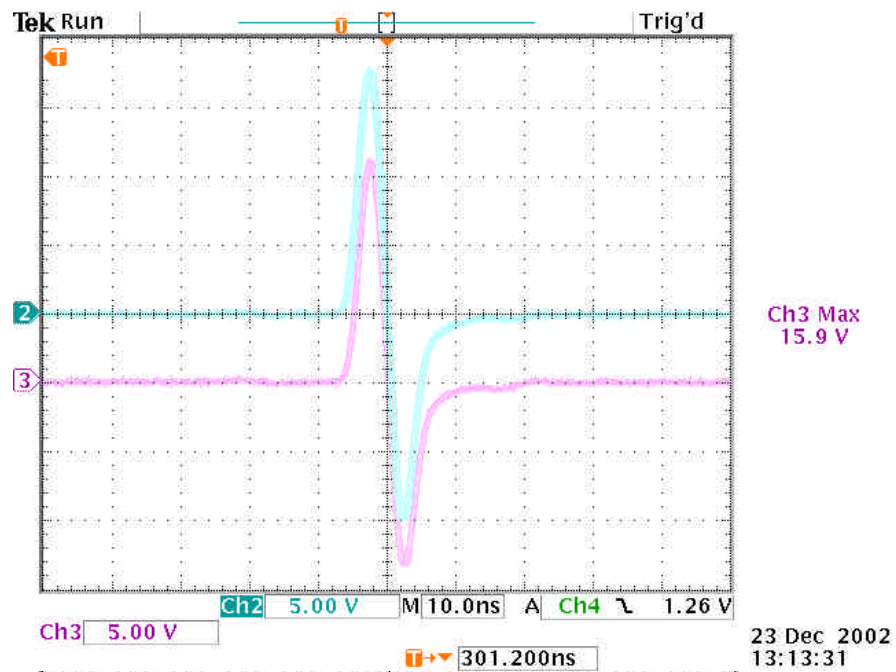
# Backup Slides



- Signal on proton end from proton bunch in a regular store.
- Triggered either by “intensity signal” or by a TeV marker???
- Very little ringing.
- FWHM of positive piece is about 4 ns.
  - Gaussian:  $\sigma \approx 1.7$  ns.
- Scope picture from Fritz D.
  - Uses HPA17
  - Signals on cables in house.
  - No filters or attenuators

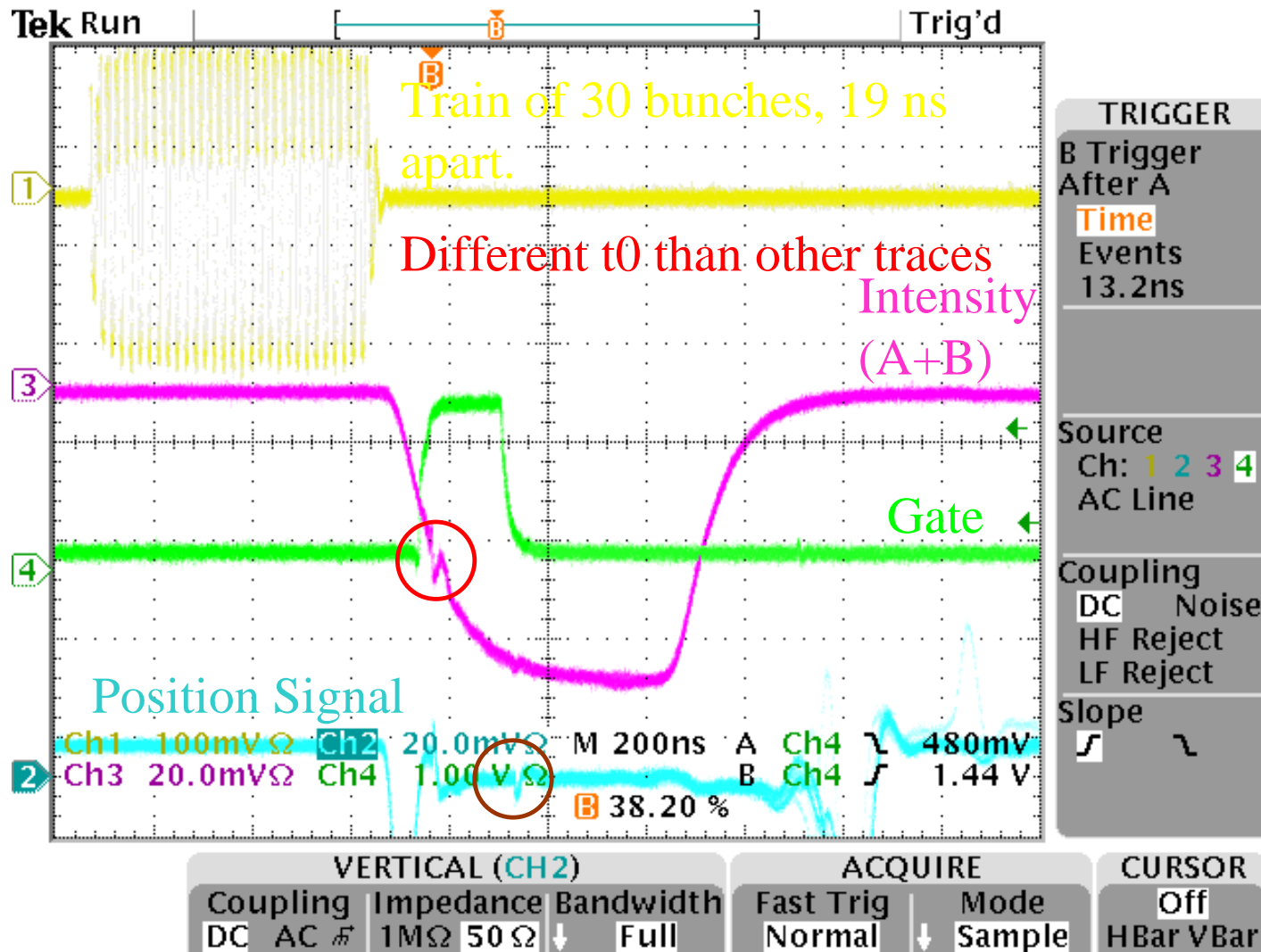


- Signal on anti-proton end induced by the proton bunch.
  - Triggered same way as previous slide.
  - Unsure how to interpret timing wrt previous slide.
- As before:
- Very little ringing.
  - FWHM of first negative piece  $\approx 4$  ns.
- Scope picture from Fritz D.
    - Uses HPA17
    - Direct from cables in house.
    - No filters or attenuators



## Comments for Next Slide

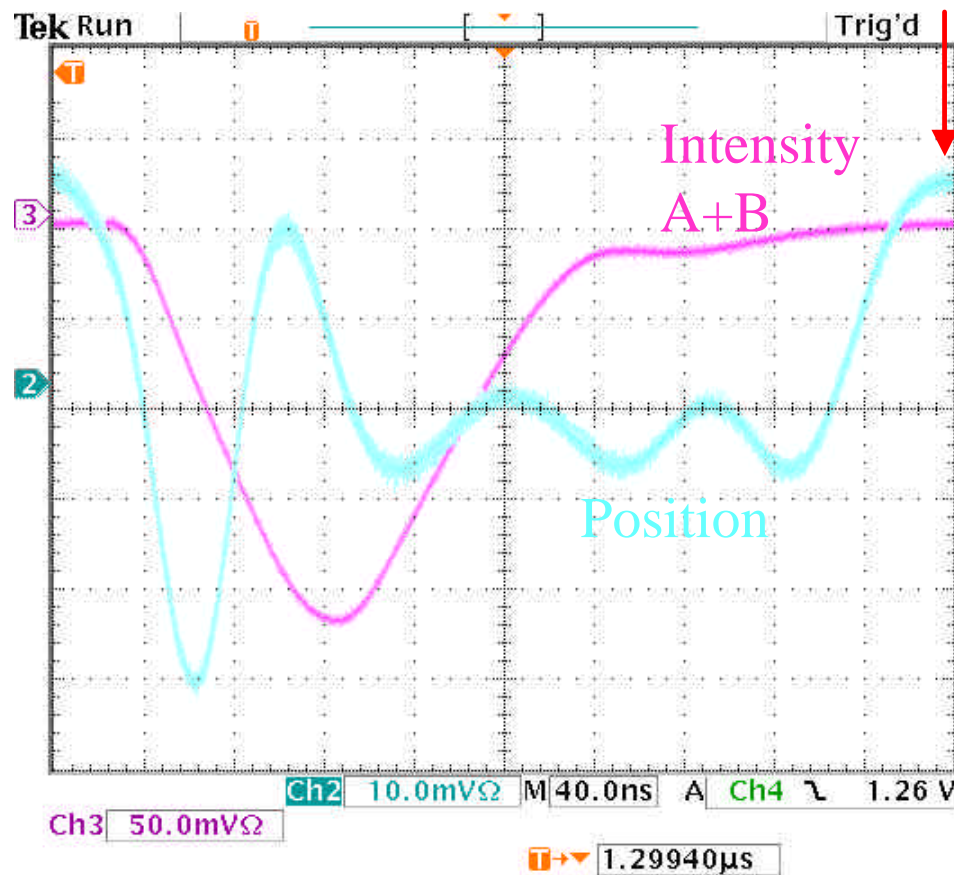
- This is a scope picture showing the response of a BPM to a train of about 30 uncoalesced bunches.
- Top trace shows signal on cables
- Bottom 3 traces characterize BPM response.
  - These are all in time wrt each other
  - The top trace has an unknown time shift.



## Notes on Previous Slide

- The bottom 3 traces have the same timing.
  - The top trace should shift to the right by ??? ns.
- Rise time of intensity signal is about 200 ns.
- Gate internally generated by threshold on intensity signal. (circled glitch)
- Is gate width programmable????
- Position Signal:
  - Overshoot at small time.
  - Position signal stable after about 200 ns.
  - Sample and hold on falling edge of gate (circled glitch)
  - Why is overshoot at end not in the opposite direction from that at start?

# BPM Response to a Single Coalesced Bunch



Next bunch comes at this time ( 396 ns ).

Does this signal ring at longer times?

- Scope picture from Fritz D. ( HPA17 ).
- Before removal of PSD boards. Now ringing in position signal is less.

23 Dec 2002  
12:52:13

# Comments on Previous Slide

- Intensity Signal
  - Rises to peak in 80 ns
    - Much faster than batch mode.
    - Conclude: this signal is never fully developed.
- Is there ringing at larger times – if so, then one bunch talks to the next bunch.
- Position Signal:
  - Overshoot has same width as for batch mode.
  - Never really gets flat.
    - Integration time of sample+hold  $\approx$  a few ns.
  - When does sample and hold take place? Earlier than for batch mode?

# Constraints

- Two Possible answers:
  1. As short as possible to separate protons and anti-protons in the time domain.
  2. It does not matter so long as the center frequency is a harmonic of the shortest possible bunch spacing. It can even have significant power after the next bunch has already arrived.
    - This talk will concentrate on explaining how this works.